LCA Case Studies

Life Cycle Assessment for the Implementation of Emission Control Measures for the Freight Traffic with Heavy Duty Vehicles in Germany

Phase 1: Life Cycle Inventory Analysis *

Luis Bárzaga-Castellanos[1], Ronald Neufert[2] and Bernd Markert[1]**

[1] International Graduate School Zittau, Environmental High Technology, Markt 23, D-02763 Zittau, Germany
(Present address: Siemens AG, CT IF I & E, D-81730 München, Germany; e-mail: luis.barzaga@mchp.siemens.de)
[2] Siemens AG, Power Generation, Redwitz Ceramics and Porcelain Business Unit Catalyst Division, Bahnhofstr. 43,
D-96257 Redwitz, Germany; e-mail: ronald.neufert@red1.siemens.de

**Corresponding author: Bernd Markert, International Graduate School Zittau, Chair of Environmental High Technology, Markt 23,
D-02763 Zittau, Germany; e-mail: markert@ihi-zittau.de

Abstract. The Life cycle inventory analysis (LCI) for the freight traffic with heavy duty vehicles in Germany was determined for the reference year 1995 and the target year 2010 by application of ISO 14040 and ISO 14041. Based on these results and under consideration of the dynamic development of road freight traffic with German heavy duty vehicles of >14 t max laden weight and composition of the German heavy duty vehicles fleet in this class the LCI for the introduction of various scenarios for reducing emissions from freight traffic was generated. Special emphasis was placed in the determination of the LCI for the implementation of primary, secondary and a combination of primary and secondary emission reduction measures for heavy duty diesel engines such as variation of diesel fuel characteristics, engine-based measures for exhaust gas optimisation, urea selective catalytic reduction (SCR) process with and without fuel consumption optimised diesel engines and particulate trap for exhaust gas optimised diesel engines with low sulphur diesel fuel. The overall environmental effects of the investigated measures on the other phases of the product life cycle of the freight traffic with heavy duty vehicles and on associated and new products to be introduced was included in the generated results for the LCI of each variant. For the implementation of the urea SCR process the results are based on manufacturer data for the overall production process of SCR honeycomb catalysts and SCR application measurements in engine and field test after a travelled distance of between 187,825 and 325,178 km under road traffic conditions with typical EURO 2 standard diesel engines for heavy duty vehicles with a max laden weight of >32 t under control of and data certification by TÜV Automotive Bayern Sachsen GmbH.

Keywords: Diesel engines; diesel fuel-based measures; engine-based measures; freight traffic; heavy duty vehicles; life cycle inventory analysis; nitrogen oxides; particulate trap; SCR catalysts; urea selective catalytic reduction process

Introduction

The EURO 3 limits for heavy-duty vehicles can only be met by means of a ≥5 [%] increase in diesel engine fuel consumption, which means that exhaust-gas cleaning measures are imperative for achieving the planned EURO 4 limits. The urea-SCR process represents the most advanced alternative, requiring no changes in the diesel fuel currently commercially available in the European Union. At the same time, this process provides a solution to the diesel dilemma, since optimized diesel engine fuel consumption settings (fuel consumption reduction ≥10 [%]) also allow a decrease in particles, HC, CO_2 and NO_x emissions. This life cycle inventory analysis (LCI) examines various measures for reducing emissions of heavy-duty vehicles used for freight traffic based on the status in the reference year of 1995. This LCI is based on the requirements of ISO 14040 and ISO 14041 for the definition of goal and scope of LCAs, and LCIs. A critical review to ISO 14040 has not yet been performed. The objective of this publication is therefore to present the results achieved to interested professionals and parties, thus enabling a critical evaluation of these results as the first step in a critical review.

1 Methodological Framework

1.1 Objectives of study, functions and functional units

The goals of this LCI are as follows:

1. Determination of realistic introduction potentials for measures for emissions reduction.
2. Determination of the effects of these measures on other phases of the product life cycle and on associated and new products to be introduced.
3. Investigation of the suitability of these measures.
4. Elaboration of proposals for optimized allocation of various measures to achieve optimum reduction in environmental impact from both ecological and economic standpoints.
5. Consideration of dynamic development of road freight traffic in points 1 to 4.
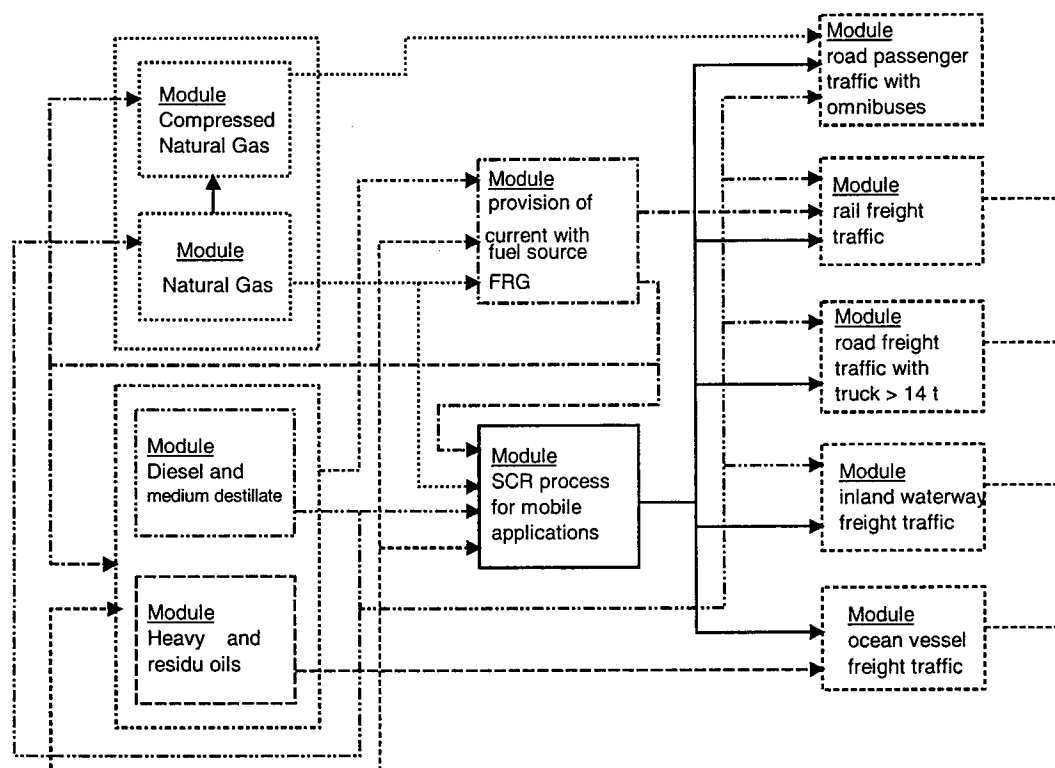
Fig. 1: Simplified system flow diagram for the reviewed product system

This LCI is intended for the active participants (direct or indirect) involved in the product life cycles of the various transport systems for freight traffic. With reference to the goals of the present life cycle assessment (LCA), this requires consideration of the following functions:

1. Achievement of transport capacity by the heavy-duty vehicle transport system.
2. Environmental impact of 1.
3. Decreased or increased loads on the environment resulting from the measures for emissions reduction, and environmental protection costs incurred.
4. Ecological effectiveness (EE) and category indicator effectiveness (CIE_j) which can be achieved with 3.

In addition, the function of the energy conversion chain for provision of the final energy carrier for the heavy-duty vehicles and the associated environmental impacts are presented as secondary environmental impacts for the reference and target years. Traveled distance [km] was specified as the functional unit for representing traffic capacity. Energy consumption in [kWh] is the functional unit and allocation procedure for conversion of the primary energy carrier to final energy. [g/km] or [kWh/km] are used as the functional units for emissions and fuel consumption for the heavy-duty vehicle pool available in the reference year and estimated for the target years. Correspondingly, the functional unit for emissions reduction measures is conversion in [%] relative to the associated diesel engine emissions category as cited in the literature or obtained from experimental results achieved in non-steady state operation. Overall emissions ([g], [m³], [Bq], etc.) or overall consumption ([kWh], [g], [MJ], [m²], etc.) in a data category for the reference and target years

relative to the corresponding distance traveled [km] are used to represent the existing emissions reduction or savings potentials and to allow a comparison of measures introduced for emissions reduction in a transport system. The entire product life cycle of 2,000 m³ SCR catalysts as the core component of the SCR process served as the basis for comparison between the various variants for introducing the SCR process. The service period of SCR catalysts was calculated for the corresponding variants on the basis of the reference designs for the variants of a typical EURO 2 standard 12 liter, six-cylinder diesel engine with turbocharging and intercooling, and the results of the real operation from the field test presented in Section 2.3. The required number of SCR systems and hence the required volume of SCR catalysts were calculated for the various variants on the basis of the determined service period of the SCR catalysts for given diesel power, annual travel distance and anticipated technical service life of the SCR systems. This in turn determines the effects of the various variants on the other phases of the PLC of the SCR systems as a functional unit in [g/number of measures]. The number of SCR systems for each variant [number] and thus the required volume of reactors for the overall service life of an SCR system is used as allocation procedure. The currency of Germany [DM] serves as the functional unit for determining the entire environmental protection costs or savings resulting from the corresponding measures in comparison with a reference measure. The functional units for the ecological effectiveness (EE) and category indicator effectiveness (CIE_j) are the units of decrease or increase in environmental loading for the various evaluation procedures and the category endpoints relative

to the total environmental protection costs of the various measures. The correlations between the functional units and the number of required products (heavy-duty vehicles [number] and measures for emissions reduction [number]) for fulfillment of this functional unit were considered on the basis of the actual results achieved relative to the specified types and classes of the corresponding transport system, and are detailed in **Appendix 1**. The 'number of measures [number]' line of the reference measure means the total number of heavy-duty vehicles required for fulfilling the functions transport capacity [km], the resulting overall environmental impact (emissions and consumption potentials) and environmental protection costs for the specified types and classes in this transport system during the specified reference time frame, because these measures have an immediate effect on all heavy-duty vehicles. In contrast, for the remaining measures, this line means the number of heavy-duty vehicles from the overall pool which are equipped with the corresponding measures during their service life as the reference time.

1.2 Specification of preliminary system boundaries

The following unit processes were included in the model for achieving the specified goals of the LCI:

1. Conversion of primary energy carrier to final energy and associated environmental impact.
2. Capacity (distance) of the various transport system and their environmental impact.
3. Measures for emissions reduction for the various traffic systems and their environmental impact.

The period covered by this study includes the reference year of 1995 and the target years 2000, 2005 and 2010. The reference time is obtained from the service period of the corresponding measure [km] based on the determined average traveled distance for the specified heavy-duty vehicle fleet [km/a]. The calendar year was selected as the reference time for the reference measure to present the initial yearly emissions and consumption potential. The geographical coverage relates to the national borders of Germany for the reference year of 1995. To be able to determine the environmental impact associated with Unit Process 1, this coverage is extended to include the suppliers of raw materials located outside Germany, because most of the raw materials are delivered from outside Germany (see **Figs. 2 to 4**). The geographical and technology coverage of Unit Process 3 for freight traffic with heavy-duty vehicles relates to the traveled distance and the composition of German heavy-duty vehicles of >14 t max. laden weight in Germany by emissions class corresponding to the existing official statistics. On the basis of the result of [1] regarding the cumulated energy demand (CED) of 8.5% $\geq CED_{H+E} \geq 5\%$ relative to the total CED for the PLC of heavy-duty vehicles, the investigation of the processes for production and disposal of the heavy-duty vehicles were not included in the system boundaries.

Special attention was given to presentation of the technology coverage with regard to a representative technological composition of the described processes relative to the mean of the actual processes. To fulfill this requirement, it is preferred to prepare the LCIs for the corresponding unit processes using those data sources for which it could be assumed that they were generated with active involvement of leading equipment manufacturers and operators, certification bodies (Technischer Überwachungsverein, German Lloyd, etc.), independent research institutes, universities and technical institutes or other federal institutions (such as the
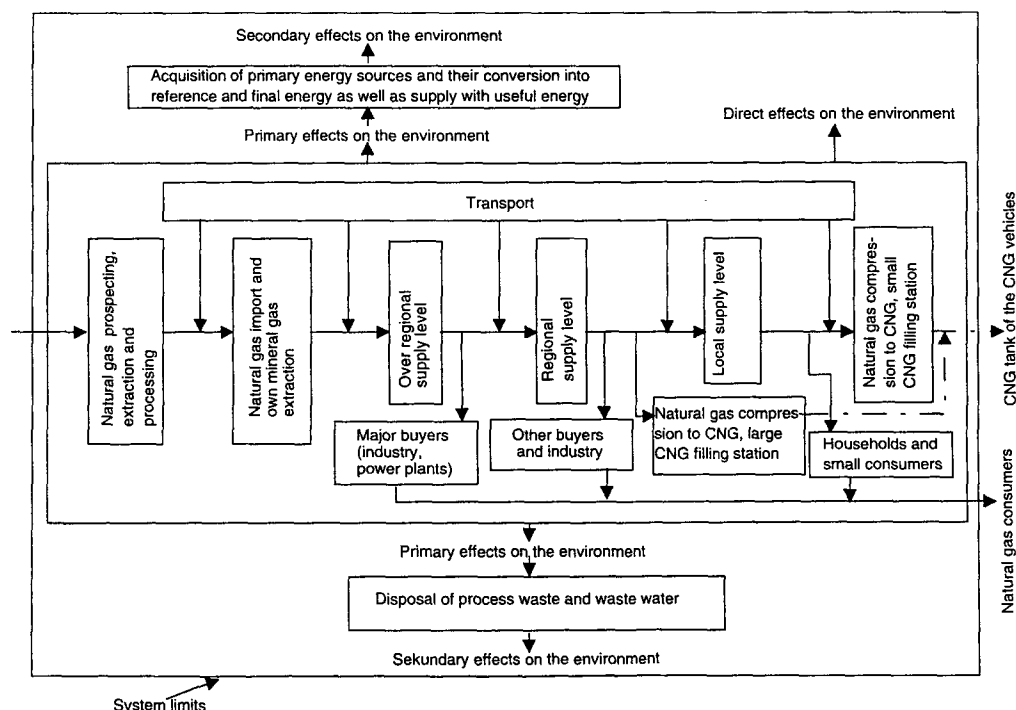

Fig. 2: System limits for analysis of making natural gas and compressed natural gas (CNG) available

German EPA, the Federal Ministry for the Environment, etc.). If the existing data do not fulfill these requirements for a specific material, a data selection is made on the basis of an intensive literature research. Data selection is not solely performed according to the smallest deviation from the mean; instead large significance is also attached to the age and source of the data, the method of determination and reliability, the state of the art and latest findings in the associated field. This is supplemented with data from the official statistics for the processes to be described as a basis for calculating and reviewing data modeling and application of existing models. In applying modeled data based on results from laboratories and test benches, it was attempted to exhaust all existing possibilities to validate these results with the results achieved under real-life operating conditions. Data selection was performed extremely carefully using all existing sources. In performing this study, the same high standards were applied to the representative nature, completeness, accuracy and currency of the data. A further objective was to ensure a high degree of consistency and traceability, and the results should therefore be made available in their entirety to interested parties.

Data validation was performed during the data collection process. For the data to be determined through our own studies for the SCR process, the validation is based on mass and energy balances and by comparison with existing energy, water, sewage, emissions measurement and waste reports. In addition, the results from the engine test bench for the reduction of emissions from diesel engines by means of the SCR process were validated by the results from non-steady state operation in road traffic. The data originating from literature sources were validated in line with the require-

ments for data quality. In this context, the causality of data gaps is investigated by strict application of the calculation methods for the LCI as per the current knowledge while the LCI is being performed. This process is performed using mass and energy balances, comparison of emission factors, results on emissions reduction for alternative measures and data in existing literature sources for the corresponding processes with each other or with processes based on similar technologies. The LCIs were prepared on the basis of the concept of 'ecological scarcity' (cf. [2]) with application of the following methods as aids and a strict classification of environmental impacts in direct and secondary environmental impacts:

- Method of process chain analysis
- Method of input-output analysis (process-based)
- Method of cumulated energy demand.

In accordance with the process chain analysis, the sequential method is used as the calculation algorithm. The nature of this approach means that iterations or recursions are generated within a process chain which significantly increase the calculation time and effort. This drawback can be compensated by investigation of the effects of individual process steps on the overall result since such iterations only make sense if the corresponding process steps have a decisive effect on the quality of the overall calculated result. The LCI performed as part of the present LCA includes all of the data categories within the specified system boundaries which are detailed in the Appendix, because it is not possible to make an *a priori* decision regarding the significance and individual influence of a process step on the final result of the LCI for one or more data categories. Whether or not a process step is relevant for the result of the LCI is determined via the sensitivity analysis for the final result of the LCI by
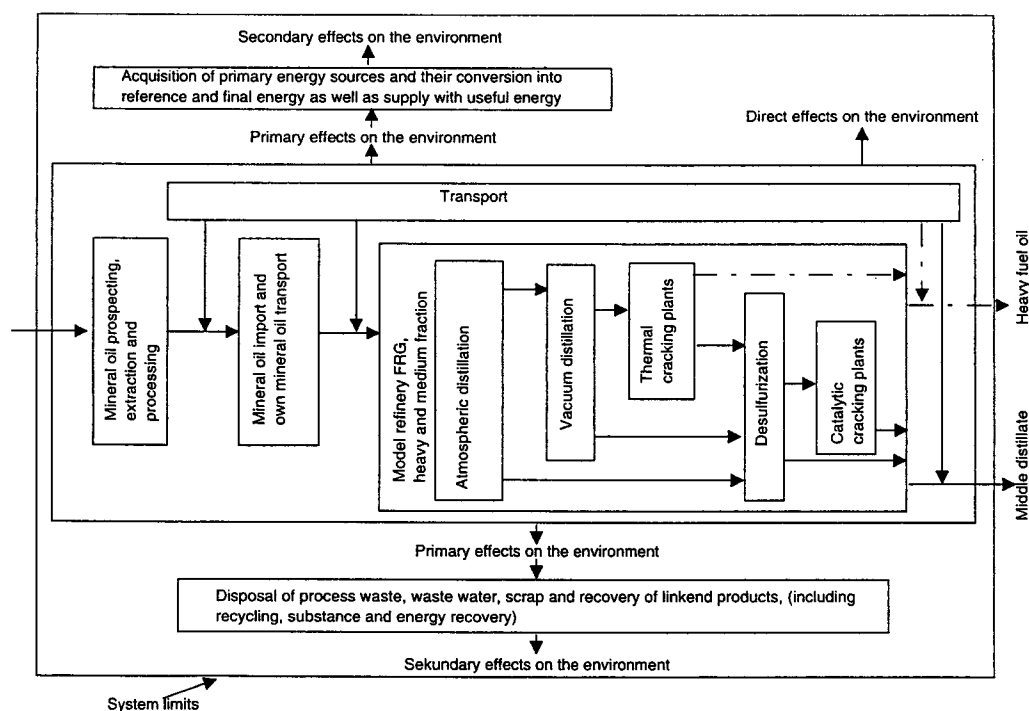

Fig. 3: System limits for the life cycle inventory analysis for making Diesel (medium distillate) and heavy oils available

systematic elimination and consideration of this process step in the entire process chain. Separate compilation and calculation of the direct and secondary environmental impacts simplifies the sensitivity analysis and accounts for its requirements from the start as well as during the entire process of conducting the LCI. The advantage of this decision method is its systematic approach instead of random determination of a limit for quantitative evaluation of data quality. Disadvantages are:

- The assumption of a clear description of the defined system boundaries, the considered processes and the procedure for conducting the LCI.
- An extensive database as prerequisite for the application of preliminary values for the performance of sensitivity analyses, as otherwise the requisite analytical capacity for the sensitivity analysis is very high and is associated with a correspondingly high degree of effort.

The objective of the sensitivity analysis as a descriptive procedure is the differentiation between important and unimportant inputs instead of a quantification of the overall inaccuracy for the system under study. This procedure yields the following possibilities for a sensitivity analysis when conducting an LCI for the entire process chain:

1. The influence of direct and secondary environmental impacts can be presented separately for all processes in the entire process chain.
2. This enables determination not only of the processes with decisive effects on the overall result of a specific environmental impact in a data category, but also of the site where the impacts arise i.e. in the core process itself or in a lower-tier subprocess.

3. This understanding is important not only for the sensitivity analysis, but rather also for evaluating of the possibilities for the implementation of environmental-protection measures and their effects and utility from the standpoint of a core process.
4. This procedure also offers the possibility of comparing the direct environmental impact on the core process with the entire secondary and/or indirect environmental impact of the entire process chain. This enables determination and evaluation of the effects of measures in the core process in comparison with the resulting environmental impact of the remaining processes of the chain.

Since a life cycle inventory analysis is an iterative process and the system boundaries to be considered can shift over the course of its performance, after the first iteration only those data in a category are investigated more closely which have exhibited significance for the overall result. As a general rule, the 95% confidence intervals are generated for estimating the statistical variance as a means of estimating a high or low degree of inaccuracy in the results. If the standard deviation is not known for the inputs and outputs, this is analyzed by changing the data by 5 [%] and considering the effects on the final LCI result. If these data are known, it is attempted, for those data which are decisive for the overall result, to present the effect of their change on the overall result by means of the values with the widest range of scatter about the mean. By taking this approach after the performance of the LCI, it was determined that the largest influences on the overall result of the LCI are caused by the effectiveness of the investigated measures for emissions reduction. Conversion [%] for the best alternative measures was therefore normalized to
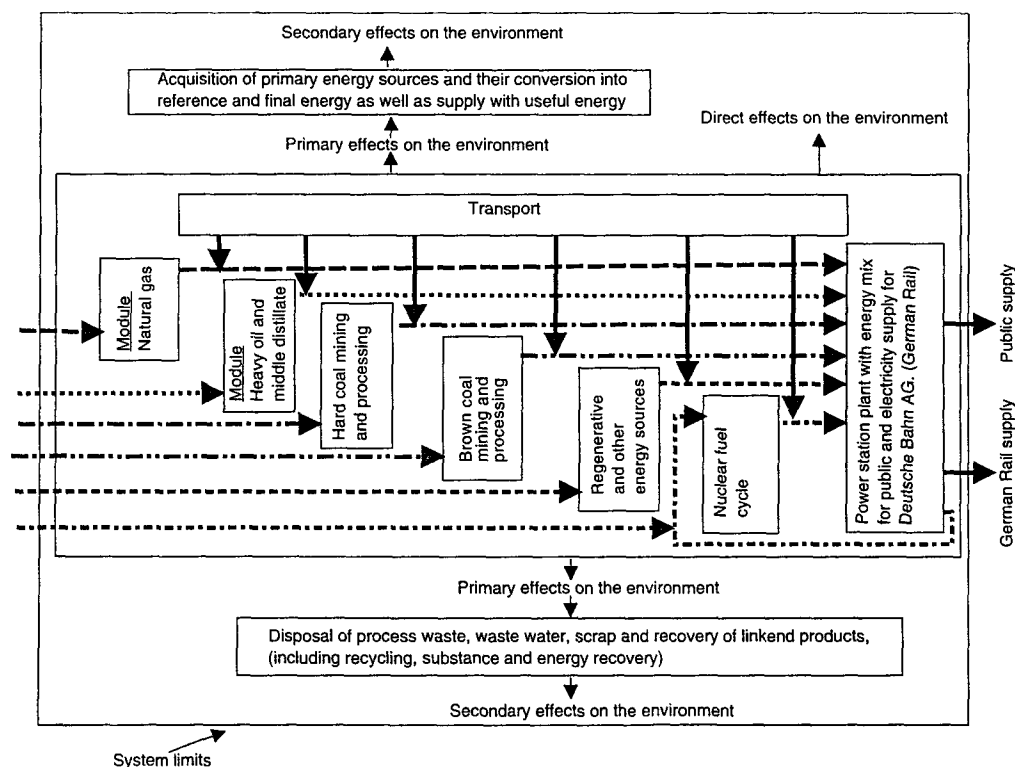

Fig. 4. System limits for the analysis of electrical energy available for public supply and supplying the Deutsche Bahn AG (German rail)

a scale of 1 and reduced to 15 [%] in steps of 5 [%]. These measures were subsequently compared with the other measures. As no changes in the order of the alternatives available for selection could be determined and the emissions reduction scatter ranges of the results from the engine test bench as well as those measured under non-steady-state operating conditions lie within the aforementioned range, the sensitivity analysis was aborted at 15 [%] (**Appendix 1**). In addition, the introduction of measures for emissions reduction in the investigated heavy duty vehicle categories causes an increase in the influence of secondary environmental impact with increasing effect of the measures and/or with increasing fuel savings or consumption.

2 LCI for Heavy-Duty Vehicle Freight Traffic in Germany

2.1 Calculation of emissions for reference year 1995

The presentation of vehicle levels and the number of heavy-duty vehicles above 14 t max. laden weight for freight traffic in Germany in the reference year 1995 is based on the data from [3], [4], [5] and [6]. The traffic capacities for the various vehicle categories were determined based on the data from [5] and [6]. Goods vehicle capacities were classified in accordance with [7]:

$$FL_{s, tp, ln, ag} = FL_{tp} * A_s(tp) * A_{s,g}(ln) * A_{s,tp}(ag) * A_{s,tp,ln}(vz) \quad \text{Eq. 1}$$

According to [5], the 'mean loading for all trips (trips with and without load)' related to the transport capacity in [%] in 1995 was 44.3 for non-trailer trucks; 43.5 for trailer trucks and 49.8 for semitrailers. Emissions from freight traffic with heavy-duty vehicles were calculated with **Equation 2** on the basis of [8,3,7,9, Vol. 6]. An extensive description of this test program is given in [3]. These results were verified using [10] as the basis for comparison.

$$e_{s,tp,ln,ag} = \sum_{vz=1}^{4} \sum_{ln=0}^{>6\%} \sum_{ek=0}^{4} \sum_{ag=0}^{100\%} e_{s,tp,ln,vz,ek,ag} *$$

$$A_{s,tp,ln}(vz) * A_{s,g}(ln) * A_{tp}(ek) * A_{tp}(ag) \quad \text{Eq. 2}$$

2.2 Primary measures for emissions reduction

2.2.1 Variation of fuel characteristics

The literature contains a series of studies completed (cf. [11-14]) or in progress (cf. [15]) of the influences of cetane number, cetane index, total aromatics, polyaromatics, final boiling point (T90 or T95) and the use of ignition accelerators to increase the cetane number of base fuels on the exhaust emissions from diesel engines.
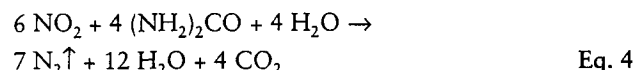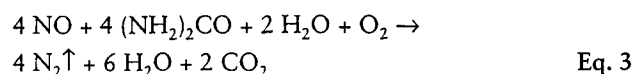
2.2.2 Engine-based measures for exhaust gas optimization of goods vehicle engines

The literature contains a series of studies (cf. [16] to [19]) of the influence of engine-based measures on exhaust emissions from diesel engines. Special attention should be given to the connection between the reduction in fuel consumption, and in particle, CO_2, CO and HC emissions and the resulting

increase in NO_x emissions from optimization of diesel engine fuel consumption.

2.3 Secondary Measures for Emissions Reduction

An extensive presentation of the urea-SCR process for diesel engines and details of its operating principles can be found in [17] to [21]. The following theoretical balance equations are obtained for this process:

$$4 \text{ NO} + 4 \text{ (NH}_2)_2\text{CO} + 2 \text{ H}_2\text{O} + \text{O}_2 \rightarrow$$
$$4 \text{ N}_2\uparrow + 6 \text{ H}_2\text{O} + 2 \text{ CO}_2 \qquad \text{Eq. 3}$$

$$6 \text{ NO}_2 + 4 \text{ (NH}_2)_2\text{CO} + 4 \text{ H}_2\text{O} \rightarrow$$
$$7 \text{ N}_2\uparrow + 12 \text{ H}_2\text{O} + 4 \text{ CO}_2 \qquad \text{Eq. 4}$$

As all NO_x emissions in the exhaust gases of diesel engines consist of ≥ 98 [%] NO, the calculation in the following investigation is based on NO. Investigations to date involving measurements on the engine test bench and in road traffic experiments focused on typical EURO 2 standard 12 liter, six-cylinder diesel engines with turbocharging and intercooling for heavy-duty vehicles in the heavy duty vehicle classes with a max. laden weight of 32 to 40 [t] for trailer trucks and >32 [t] for semi trailers (cf. [17] to [21]). After a total traveled distance of between 187,825 and 325,178 [km] in field tests in actual freight operations under the control of and data certification by TÜV Automotive Bayern-Sachsen GmbH, a range of between 60 and 80 [%] was measured for NO_x reduction rate with the SCR system, with an average value of 65 [%] (cf. [17] to [21]). The error threshold of the measurements was evaluated at ±2 [%]. An extensive description of the LCI for the SCR honeycomb catalyst manufacturing process is given in [22]. The LCA performed for the product life cycle of SCR catalysts for mobile applications was analogous to that in [22]. The secondary environmental impact of the SCR process include the processes of steel and $(NH_2)_2CO$ production for constructing the SCR reactor and selective catalytic reduction of NO_x and the process chain of transporting the SCR systems from manufacturing sites to the implementation site during manufacturing or equipping the engines (Fig. 5).

2.4 LCI of overall environmental effects

1995 scenario: The direct environmental impacts of heavy-duty vehicle freight traffic for this scenario were determined with the following equations:

$$e_{tp} = \sum_{s=1}^{6} ((e_{s,tp,ln,ag}) *$$

$$A_{s,tp,ln,ag}(FL)) \qquad \text{Eq. 5}$$

$$E_{tp} = \sum_{s=1}^{6} ((e_{s,tp,ln,ag}) *$$

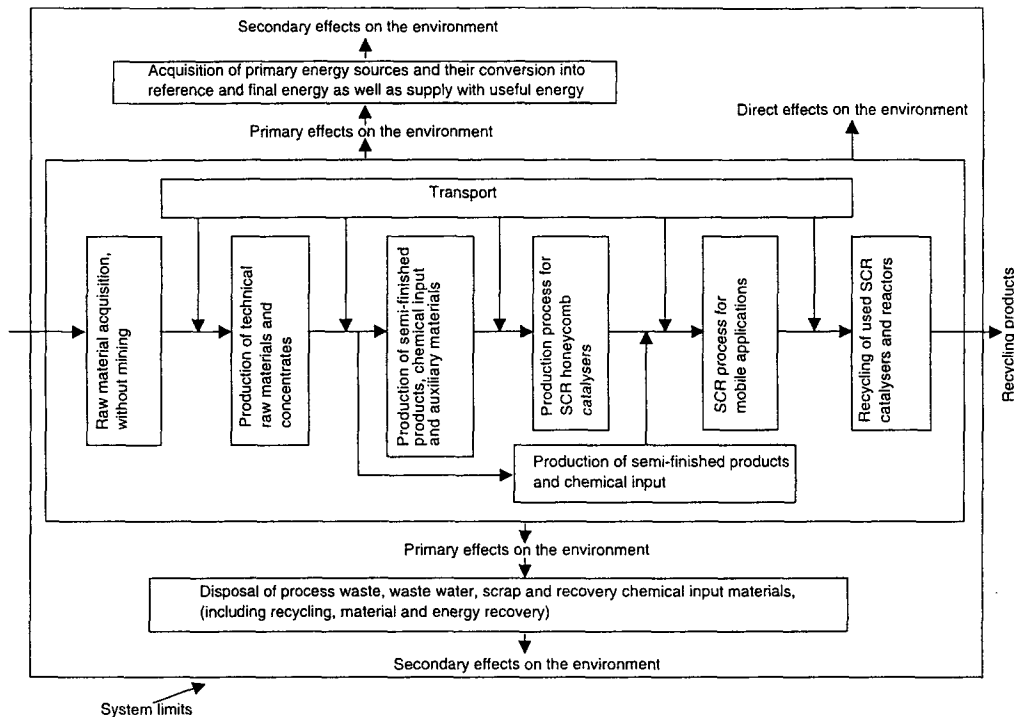$$FL_{s,tp,ln,ag}) \qquad \text{Eq. 6}$$

Fig. 5: System limits for the analysis of the SCR process for mobile applications

$$E = \sum_{tp=1}^{3} \sum_{s=1}^{6} \left(F \cdot L_{s,tp,In,ag} * e_{s,tp,In,ag} \right) \qquad \text{Eq. 7}$$

Emissions from freight traffic have changed with the introduction of fuel-side measures as a result of the introduction of new diesel fuels after October 1995 and the change in the number of heavy-duty vehicles without any change in engine specifications (EURO 2). The yearly change in numbers and the annual replacement were therefore determined from statistically reliable data on the registration of brand new heavy-duty vehicles and the yearly inventory of heavy-duty vehicles (cf. [9, Vol. 8, pp. 41-44 and Vol. 1, pp. 52-59]). The calculated annual replacement factor of 8 [%] for trucks > 12 t and 12 [%] for truck tractors >12 t were taken as a reference point for estimating the yearly increase in low-emissions heavy-duty vehicles in these emissions classes. These values agree sufficiently well with the yearly change in numbers of low-emissions heavy-duty vehicles determined from the statistical data on the number of low-emissions heavy-duty vehicles up to the last year of data acquisition (1997) (cf. [9, Vol. 6, pp. 104 to 106]). The number of low-emissions heavy-duty vehicles by emissions class in 1997 was used as the starting point for estimating pool growth for the specified reference years 2000, 2005 and 2010. The results from [23, p. 95] regarding the development of traffic capacity in [vehicle km] were used as the basis for estimating emissions from freight traffic for the analysis reference years.

Fuel scenario: Quantification of the components of individual fuels on the diesel market after 2000 is associated with a

high degree of uncertainty and is not performed in this study. The effects of the fuel proposed by the European Union Commission (EU2000, cf. [24]) on PM and gaseous emissions from heavy-duty vehicles are taken as the basis for calculating the direct environmental impact of freight traffic following implementation of fuel side measures. Reduction in emissions from EURO 2 diesel engines by 2.15 [%] for NO_x, 0.39 [%] for CO, 2.20 [%] for hydrocarbons and 3.22 [%] for particles was specified for calculating this scenario for the introduction of this diesel fuel in comparison with the base fuel from October 1995. It should be noted in this connection that, in comparison with the diesel fuel before October 1995, introduction of the base diesel fuel after October 1995 already resulted in the following emissions changes:

For EURO 1 diesel engines:
  23 to 44 [%] reduction in particles and
  3.0 [%] increase in NO_x,

For EURO 2 diesel engines:
  67.5 [%] reduction in CO,
  90.5 [%] reduction in hydrocarbons
  34.5 [%] reduction in particles and
  19.0 [%] increase in NO_x.

The reduction in sulfur content in the fuel from an average of 1,500 [mg/kg] before October 1995 to 381 [mg/kg] for the diesel fuel valid in the EU since October 1995 is also accounted for in the calculation of SO_2 emissions.

$$\Delta e_{M,i} = \frac{(e_{M,(i-1)} - e_{M,i})}{e_{M,(i-1)}} \qquad \text{Eq. 8}$$

$$c_{s,tp,\ln,ag,M,j} = \sum_{v=1}^{4} \sum_{\ln=0}^{>6\%} \sum_{ek=0}^{4} \sum_{ag=0}^{100\%} e_{s,tp,\ln,v,ek,ag} * \Delta e_{M,j} *$$

$$A_{s,g}(\ln) * A_{tp}(ek) * A_{tp}(ag) \qquad \text{Eq. 9}$$

Absolute emissions or the absolute reduction in emissions and fuel consumption are determined analogous to Equations 8 and 9 by inserting e in Equations 6 and 7 *for all scenarios.*

EURO 3 scenario: Approximate derivation of an LCI for road freight traffic with special consideration of engine measures for emissions reduction requires the following:

• Consideration of emissions reduction results with engine measures for EURO 1 and EURO 2 diesel engines.
• Consideration of requirements specified and feasible by means of engine measures for diesel engines according to EURO 3 emission standard for heavy-duty vehicles.
• Estimation of the anticipated development in the number of low-emissions heavy-duty vehicles in the aforementioned emission classes.

The date for implementation of the EURO 3 standard (from January 1, 2000) as agreed by the European Council of Environmental Ministers on December 21, 1998, was specified for estimation of anticipated development in the number of EURO heavy-duty vehicles. The development in numbers was subsequently estimated as for the 1995 and fuel scenarios with a annual replacement factor of 8 [%] for trucks >12 t and 12 [%] for truck tractors >12 t. This procedure also holds for scenarios 1 and 2 (V_1 and V_2). A 5 [%] increase in fuel consumption for EURO 3 engines over that of EURO 2 engines was estimated in the calculations.

Scenario 1 (variant V_1): Aftertreatment of the exhaust gases from brand new heavy-duty vehicles >14 [t] with exhaust-gas optimized EURO 2 engines with an SCR system starting from the year 2000 and use of the diesel fuel valid in the EU since October 1995. Using EURO 2 as a basis, this scenario takes a reduction in exhaust emissions after SCR treatment of 70 [%] for NO_x, 77 [%] for hydrocarbons (HC) and 18 [%] for particles (PM) as the calculation basis. This scenario corresponds to the achieved goal of SCR development for NO_x in exhaust-gas optimized diesel engines and the engine test bench results achieved to date with the ETC test cycle for HC and PM (cf. [19]).

Scenario 2 (variant V_2): Fulfillment of emissions reduction results of EURO 4 standard EEVs for CO, HC and PM with the use of a consumption-optimized diesel engine starting from the year 2000 for brand new heavy-duty vehicles >14 [t] with fuel savings of 10 [%] over EURO 2 engines and subsequent reduction in increased NO_x emissions from 12 [g/kWh] to 2 [g/kWh] by SCR aftertreatment of the engine exhaust gases. Contrasted with the EURO 2 limits, this scenario corresponds to a reduction in exhaust emissions by 72 [%] for CO, 72 [%] for NO_x, 92 [%] for PM and 77 [%] for HC relative to the ETC test cycle and an additional 10 [%] reduction in CO_2 and SO_2 emissions due to the 10 % fuel savings, without changing the fuel parameters for the diesel fuel valid in the EU since October 1995 (cf. [18]).

Scenario 3 (variant V_3): Fulfillment of emissions reduction results for EURO 4 standard EEVs for CO, HC and PM with the use of a consumption-optimized diesel engine starting in 2005 for brand new heavy-duty vehicles >14 [t] with fuel savings of 10 [%] over EURO 2 engines and subsequent reduction in increased NO_x emission from 12 [g/kWh] to 2 [g/kWh] by SCR aftertreatment of the engine exhaust gases. Contrasted with the EURO 2 limits, this scenario corresponds to a reduction in exhaust emissions by 72 [%] for CO, 72 [%] for NO_x, 92 [%] for PM, 77 [%] for HC relative to the ETC test cycle and an additional 10 [%] reduction in CO_2 and SO_2 emissions due to the 10 % fuel savings, without changing the fuel parameters for the diesel fuel valid in the EU since October 1995 (cf. [18]). The date for implementation of the EURO 4 standard (from 2005) as agreed by the European Council of Environmental Ministers was specified for estimation of the anticipated development in the number of heavy-duty vehicles for scenarios 3 and 4 (V_3 and V_4). As with the other scenarios, a portion of the yearly replacement of 8 [%] for trucks >12 t and 12 [%] for truck tractors >12 t was subsequently estimated for the development in numbers.

Scenario 4 (variant V_4): Fulfillment of emissions reduction results of EURO 4 standard B for NO_x with an exhaust-gas optimized diesel engine starting in 2005 for brand new heavy-duty vehicles >14 [t] with an increased fuel consumption of 7 [%] over EURO 2 engines and subsequent reduction of the increased PM, CO and HC emissions by aftertreatment of the engine exhaust gases with a particulate trap. In contrast with the EURO 2 limits, this scenario corresponds to a reduction in exhaust emissions by 96 [%] for CO, 51 [%] for NO_x, 92 [%] for PM and 98 [%] for HC relative to the ETC test cycle and an additional 7 [%] increase in CO_2 emission over a EURO 2 engine due to the 7 % increase in fuel consumption [cf. [25]]. The use of particulate traps presumes a reduction in fuel sulfur content for the diesel fuel valid in the EU since October 1995 from an average of 381 [mg/kg] to 10 [mg/kg] for EC1 diesel fuel. This results in a reduction in direct SO_2 emissions by an average of 97.38 [%]. Reliable data regarding composition and production or preproduction and production of the input materials for the scenario are not known. The particulate trap system is therefore not included in the inventory analysis.

The development of emissions results in the individual scenarios are shown in Appendix 1. For performance of the LCIs for the scenarios, it was specified that there be no significant change in serviceability of the engine-side measures over the entire service period of the heavy-duty vehicles. The exhaust-gas side measures assume a technical service period of 500,000 [km]. It was further assumed that the increasing travel distance of the entire pool of vehicles between reference years 2000 and 2010 would result in no significant change in the total number of vehicles, but rather would be achieved by a slight increase in annual distance traveled per vehicle. The results from scenarios 1 and 2 as well as the results from EURO 3 scenario and the results from the fuel scenario were compared to be able to perform the LCIs on the basis of the standard design for the reference year 2000. The results from scenarios 3 and 4 were compared with the

results from scenario EURO 3 to perform the LCIs on the basis of the standard design for reference year 2005. A stoichiometric ratio (α) of $\alpha = 0.71$ for an NO_x reduction (η) of $\eta = 70$ [%] and of $\alpha = 0.73$ for an NO_x reduction (η) of $\eta = 72$ [%] was used to determine NH_3 and $(NH_2)_2CO$ consumption as well as NH_3 slip. This enables calculation of NH_3 and urea consumption based on Equation 3. NH_3 slip (s) is calculated with the following equation:

$$s = \Delta e_{NO_x} * (\alpha - \eta) \qquad \text{Eq. 10}$$

To determine the environmental impact from the product life cycle of the SCR catalysts on scenarios 1, 2 and 3, the simplified assumption was made (in accordance with the current state of the art) that SCR catalysts with a volume of 33.3 [dm^3] and a 52 [kg] steel casing are required for aftertreatment of the exhaust gases of a heavy-duty vehicle. The number of SCR systems to be included in the LCI is determined on basis of the total number of heavy-duty vehicles >14 [t] max. laden weight and on the replacements on which the scenarios to be calculated were based.

Abbreviations and Symbols	
FL	Traveled distance
A(tp)	Traveled distance factors relative to vehicle type
A(ln)	Road incline factors weighted by traveled distance
A(ag)	Utilization factors
A(vz)	Traffic factors
A(ek)	Factor of vehicles in an emissions class
tp	Vehicle type index
s	Road type index
g	Vehicle group index
ln	Road incline index
ag	Index for degree of utilization
ek	Emissions class index
e	Specific basis factor for pollutant emissions or fuel consumption
Δe	Reduction of specific basis factor
E	Absolute emissions or fuel consumption
ΔE	Absolute reduction in emissions or fuel consumption
M	Index for measure with M = k (fuel-side) and/or m (engine-side) and/or SCR (selective catalytic reduction)
0	Index for starting year (1995)
j	Index for reference year with j = 1 (2000), 2 (2005) and 3 (2010)
s	NH_3 slip
S	Sulfur
SCR	Selective catalytic reduction
EEV	Enhanced environmentally friendly vehicle
η	NO_x reduction
α	Stoichiometric ratio
CED	Cumulated energy demand

References

[1] Mauch W (1993): Kumulierter Energieaufwand für Güter und Dienstleistungen -Basis für Ökobilanzen, Munich, Technical University, Diss., 1993, IfE-Schriftenreihe Heft 26. Resch KG, Gräfelfing

[2] Braunschweig A, Müller-Wenk R (1993): Ökobilanzen für Unternehmungen: Eine Wegleitung für die Praxis. Paul Haupt, Bern, Stuttgart, Vienna

[3] Hassel D et al. (1995): Abgasemissionsfaktoren von Nutzfahrzeugen in der BRD für das Bezugsjahr 1990, UFO PLAN No. 104 05 151/02. Umweltbundesamt, Berlin

[4] Kraftfahrt-Bundesamt (1996): Kraftfahrzeuge monatlich - Neuzulassungen, Besitzumschreibungen, Löschungen und Bestand, Reihe 1, Volume 12. Metzler-Poeschel, Stuttgart

[5] Kraftfahrt-Bundesamt und Bundesanstalt für Güterverkehr (1996): Verkehrsleistung deutscher Kraftfahrzeuge, Series 8. Metzler-Poeschel, Stuttgart

[6] Bundesanstalt für Straßenwesen (1997): Straßenverkehrszählung 1995 – Jahresfahrleistungen und mittlere DTV-Werte, Berichte der Bundesanstalt für Straßenwesen, Verkehrstechnik, Volume V 41. NW, Bremerhaven, Bergisch Gladbach.

[7] Regniet G, Schmidt G (1994): Nutzfahrzeug-Jahresfahrleistungen 1990 (1986) auf den Straßen der BRD, Forschung Straßenbau und Straßenverkehrstechnik Volume 674. Bundesministeriums für Verkehr (Hrsg), Aachen

[8] Infrastruktur-, Umwelt- und Verkehrsberatung (1995): Handbuch für Emissionsfaktoren des Straßenverkehrs, im Auftrag des Umweltbundesamtes Berlin (UBA) und des Bundesamtes für Umwelt, Wald und Landschaft (BUWAL) Bern, Bern, Version 1.1

[9] Kraftfahrt-Bundesamt (1995-1997): Statistische Mitteilungen, Series 1, Volume 1, 6 and 8. Metzler-Poeschel, Stuttgart

[10] Tieber J (1997): Eine globale Methode zur Berechnung des Emissionsverhaltens von Nutzfahrzeugen. Diss. Technical University Graz, Graz, Österreich

[11] Lange WW et al. (1995): Das Potential der Kraftstoffqualität für die Verbesserung von Verbrennung und Emissionsverhalten abgasoptimierter Nutzfahrzeug-Dieselmotoren. Symposium Dieselmotorentechnik, Technical Academy, Esslingen, 7./8.12.1995, p 237 ff

[12] ACEA, EUROPIA (1995): European Programme on Emissions, Fuels and Engine Technologies, Final Report (Executive Summary). Brussels

[13] Reynolds EG (1995): The Effect of Fuel Processes on Heavy Duty Automotive Diesel Engine Emissions. Society of Automotive Engineers, Inc. Warrendale, USA, SAE Paper 952350, p 13 ff

[14] Camarsa K, Hublin M, MacKinven R (1996): Impact of EPEFE Data on the European Auto-Oil Process. Society of Automotive Engineers, Inc. Warrendale, USA, SAE Paper 961076, p 209 ff

[15] EUROPEAN COMMISSION (1998): The Auto-Oil II Programme Second Contact Group Meeting, Directorate-General III, Industry, Brussels

[16] Essers U, Prescher KH (Hrsg) (1996): Dieselmotorentechnik 96 'Aktueller Stand und Entwicklungstendenzen', Volume 505, Expert-Verl., Reuningen-Malmsheim

[17] Lenz HP et al. (Hrsg) (1995 to 1999): Internationales Wiener Motorensymposium, Annual Research Report VDI Series 12., VDI-Verlag, Düsseldorf

[18] Marquardt KJ, Braun T, Binder K (1999): Ein Abgasnachbehandlungssystem für Dieselmotoren auf Basis der SCR-Technologie, In: 3. Stuttgarter Symposium 'Kraftfahrwesen und Verbrennungsmotoren', Stuttgart 23.-25. Februar 1999, expert, Reuningen-Malmsheim, p 122-139

[19] Fritz N, Mathes W, Zuerbig J, Mueller R (1999): On-Road Demonstration of NO_x Emissions Control for Diesel Trucks with SINOx Urea SCR Systems. Society of Automotive Engineers, Inc. Warrendale, USA, SAE Paper 1999-01-0111, p 1-8

[20] Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen (1998): Feldversuch mit 8 Lkw ausgestattet mit Diesel SCR System von Siemens, Final report, commissioned by: TÜV Automotive Bayern-Sachsen GmbH, Munich

[21] Hammerle RH, Ketcher D, Horrocks RW, Lepperhoff G, Hüthwohl G, Lüers B (1995): Emissions from Diesel Vehicles with and without Catalysts and Particulate Traps, Society of

Automotive Engineers, Inc. Warrendale, USA, SAE Paper 952391, p 197-215

[22] Bárzaga-Castellanos L, Neufert R, Kayser G, Markert B (1999): Life Cycle Assessment of the SCR-Process for Power Plants. Int. J. LCA 4 (6) 329-338

[23] Ratzenberger R, Hild R, Langmantel E (1995): Voraus-schätzung der Verkehrsentwicklung in Deutschland bis zum Jahr 2010, Ifo Institut für Wirtschaftsforschung (Hrsg), im Auftrag des Bundesministeriums für Verkehr. Ifo, Munich

[24] Kommission der Europäischen Gemeinschaften (1996): Mit-teilung der Kommission an den Rat und das Europäischen Parlament betreffend die künftige Strategie zur Bekämpfung

der Luftverunreinigung durch den Straßenverkehr unter Be-rücksichtigung der Ergebnisse des Auto-Öl-Programms. KOM(96) 248 endg., Brussels

[25] Bronnenberg P (1998): Antriebsysteme mit Dieselmotoren und hocheffizienten Abgasreinigungen im ÖPNV, In: 2. Nahver-kehrsforum 'Umweltgerecht und bezahlbar – Antriebskonzepte des Nahverkehrs mit Zukunft', Conference Volume 11 - 12 March 1998, Paderborn, p 59 -65

Appendix 1: Life cycle inventory analysis for the introduction of various scenarios or reducing emission

Reference data	Actual, 1995	K, 2010	K+EU3M, 2010	V₁, 2010	V₂, 2010	V₂, SP, 2010	V₃, 2010	V₃, SP, 2010	V₄, 2010
Heavy duty vehicles > 14 [t] permissible total weight	Reference year	Reference measure	Total	Total	Total	Sensitivity test	Total	Sensitivity test	Total
Fuel saving [kWh]	9.93E+10	1.19E+11	-3.19E+10	0.00E+00	6.35E+10	6.35E+10	5.72E+10	5.72E+10	-4.58E+10
NOₓ reduction [g]	0.00E+00	0.00E+00	5.77E+11	1.11E+12	1.14E+12	9.71E+11	3.49E+11	2.97E+11	1.77E+11
NH₃ consumption in (NH₂)₂CO [g]	0.00E+00	0.00E+00	0.00E+00	5.54E+11	6.58E+11	6.58E+11	4.07E+11	4.07E+11	0.00E+00
(NH₂)₂CO consumption [g]	0.00E+00	0.00E+00	0.00E+00	3.01E+12	3.58E+12	3.58E+12	2.22E+12	2.22E+12	0.00E+00
Number of measures [quantity]	0.00E+00	4.02E+05	3.68E+05	3.68E+05	3.68E+05	3.68E+05	2.20E+05	2.20E+05	2.20E+05
Price of measure [DM]	0.00E+00	0.00E+00	**1.50E+03**	**1.00E+04**	**1.00E+04**	1.00E+04	**1.00E+04**	1.00E+04	**1.00E+04**
Service life measure [km]	0.00E+00	1.00E+06	1.00E+06	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05
Ref. travel perform. with measure [km]	0.00E+00	1.00E+06	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05
Travel performance, total [km]	0.00E+00	3.48E+10	2.01E+11	2.01E+11	2.01E+11	2.01E+11	2.01E+11	2.01E+11	2.01E+11
Travel perform. with measure [km]	0.00E+00	3.48E+10	1.86E+11	1.86E+11	1.86E+11	1.86E+11	1.14E+11	1.14E+11	1.14E+11
Average travel perf. [km/heavy duty vehicles * a]	0.00E+00	8.65E+04	8.65E+04	8.65E+04	8.65E+04	8.65E+04	8.65E+04	8.65E+04	8.65E+04
Reference period [a]	0.00E+00	1.00E+00	5.78E+00	5.78E+00	5.78E+00	5.78E+00	5.78E+00	5.78E+00	5.78E+00
Operating costs [DM]	0.00E+00	1.69E+08	3.10E+09	1.50E+09	-4.39E+09	-4.39E+09	-4.46E+09	-4.46E+09	5.28E+09
Investment [DM]	0.00E+00	0.00E+00	2.76E+08	3.68E+09	3.68E+09	3.68E+09	2.20E+09	2.20E+09	2.20E+09
Capital service (8% annuity) [DM]	0.00E+00	0.00E+00	**3.55E+08**	**4.74E+09**	**4.74E+09**	4.74E+09	**2.84E+09**	2.84E+09	**2.84E+09**
Maintenance (4%/a) VDI 38000 [DM]	0.00E+00	0.00E+00	6.38E+07	8.50E+08	8.50E+08	8.50E+08	5.10E+08	5.10E+08	5.10E+08
Total costs (- for savings) [DM]	0.00E+00	**1.69E+08**	**3.52E+09**	**7.09E+09**	**1.20E+09**	1.20E+09	**-1.11E+09**	-1.11E+09	**8.63E+09**
Specific NOₓ costs (- for savings) [DM/g NOx]	0.00E+00	**0.00E+00**	**6.10E-03**	**6.37E-03**	**1.05E-03**	1.24E-03	**-3.19E-03**	-3.75E-03	**4.88E-02**
Specific costs/measures km [DM/km]	0.00E+00	**4.86E-03**	**1.90E-02**	**3.82E-02**	**6.46E-03**	6.46E-03	**-9.82E-03**	-9.82E-03	**7.60E-02**
Input:									
Land use [m³]	1.38E+06	1.65E+06	-4.42E+05	-5.40E+05	3.41E+05	3.41E+05	4.62E+05	4.62E+05	-1.32E+05
Thermal energy [MJ]	3.78E+11	4.52E+11	-1.21E+11	-1.86E+10	2.20E+11	2.20E+11	2.04E+11	2.04E+11	-3.62E+10
Electrical energy from refinery power station [kWh]	2.10E+08	2.51E+08	-6.74E+07	0.00E+00	1.34E+08	1.34E+08	1.21E+08	1.21E+08	-2.01E+07
Electrical energy from FRG supply network [kWh]	4.57E+08	5.46E+08	-1.47E+08	-2.13E+08	7.17E+07	7.17E+07	1.30E+08	1.30E+08	-4.38E+07
Transport per oil tanker [tkm]	3.07E+10	3.67E+10	-9.85E+09	-3.59E+08	1.93E+10	1.93E+10	1.75E+10	1.75E+10	-2.94E+09
Transport per pipeline [tkm]	6.73E+09	8.04E+09	-2.16E+09	0.00E+00	4.30E+09	4.30E+09	3.88E+09	3.88E+09	-6.44E+08
Transport by inland waterway vessel to customer [tkm]	9.23E+08	1.10E+09	-2.96E+08	0.00E+00	5.90E+08	5.90E+08	5.32E+08	5.32E+08	-8.84E+07
Transport by rail to customer [tkm]	3.51E+08	4.19E+08	-1.12E+08	-3.58E+08	-1.34E+08	-1.34E+08	-1.23E+07	-1.23E+07	-3.36E+07
Transport per pipeline to customer [tkm]	7.51E+07	8.97E+07	-2.41E+07	0.00E+00	4.80E+07	4.80E+07	4.33E+07	4.33E+07	-7.19E+06
Transport per truck to customer [tkm]	3.13E+08	3.73E+08	-1.00E+08	-1.33E+07	1.87E+08	1.87E+08	1.69E+08	1.69E+08	-2.99E+07
Material requirement/operating materials:									
Raw oil investment, ρ = 0.831 [t/m³], S content = 1.18 %, by weight [t]	8.39E+06	1.00E+07	-2.69E+06	0.00E+00	5.37E+06	5.37E+06	4.84E+06	4.84E+06	-8.04E+05
Fuel mix FRG [kg]	4.93E+08	5.89E+08	-1.58E+08	0.00E+00	3.15E+08	3.15E+08	2.84E+08	2.84E+08	-4.72E+07
Nuclear fuel [kg]	1.18E+03	1.41E+03	-3.79E+02	0.00E+00	7.54E+02	7.54E+02	6.80E+02	6.80E+02	-1.13E+02
TiO₂ [kg]	0.00E+00	0.00E+00	0.00E+00	6.66E+06	6.66E+06	6.66E+06	3.99E+06	3.99E+06	0.00E+00
WO₃ [kg]	0.00E+00	0.00E+00	0.00E+00	6.00E+05	6.00E+05	6.00E+05	3.59E+05	3.59E+05	0.00E+00
V₂O₅ [kg]	0.00E+00	0.00E+00	0.00E+00	9.68E+04	9.68E+04	9.68E+04	5.80E+04	5.80E+04	0.00E+00
Iron ore (FeS₂) [kg]	0.00E+00	0.00E+00	0.00E+00	1.53E+07	1.53E+07	1.53E+07	9.16E+06	9.16E+06	0.00E+00

Reference data	Actual, 1995	K, 2010	K+EU3M, 2010	V, 2010	V$_2$, 2010	V, SP, 2010	V$_3$, 2010	V, SP, 2010	V$_4$, 2010
Heavy duty vehicles > 14 [t] permissible total weight	Reference year	Reference measure	Total	Total	Total	Sensitivity test	Total	Sensitivity test	Total
CaO [g]	7.45E+09	8.90E+09	-2.39E+09	0.00E+00	4.76E+09	4.76E+09	4.29E+09	4.29E+09	-7.13E+08
NH$_3$ [g]	2,11E+08	2.52E+08	-6.76E+07	0.00E+00	1.35E+08	1.35E+08	1.21E+08	1.21E+08	-2.02E+07
Oxidation air for DeSOx [g]	1.26E+11	1.51E+11	-4.04E+10	0.00E+00	8.05E+10	8.05E+10	7.26E+10	7.26E+10	-1.21E+10
Steam for DeNOx [g]	4.50E+08	5.37E+08	-1.44E+08	0.00E+00	2.87E+08	2.87E+08	2.59E+08	2.59E+08	-4.30E+07
Process water [g]	2.55E+12	3.04E+12	-8.18E+11	4.12E+10	1.67E+12	1.67E+12	1.49E+12	1.49E+12	-2.44E+11
H$_2$O evaporation [g]	1.08E+12	1.29E+12	-3.45E+11	0.00E+00	6.88E+11	6.88E+11	6.20E+11	6.20E+11	-1.03E+11
Cooling water (supplementary water) [g]	5.50E+13	6.57E+13	-1.76E+13	0.00E+00	3.51E+13	3.51E+13	3.17E+13	3.17E+13	-5.26E+12
Cleaning water [g]	0.00E+00	0.00E+00	0.00E+00	1.20E+10	1.20E+10	1.20E+10	7.16E+09	7.16E+09	0.00E+00
Drinking water [g]	0.00E+00	0.00E+00	0.00E+00	3.03E+09	3.03E+09	3.03E+09	1.82E+09	1.82E+09	0.00E+00
H$_2$ [g]	4.95E+10	5.92E+10	-1.59E+10	0.00E+00	3.17E+10	3.17E+10	2.86E+10	2.86E+10	-4.74E+09
Output:									
Diesel fuel with 0.05 % by weight sulfur content [kWh]	9.93E+10	1.19E+11	-3.19E+10	0.00E+00	6.35E+10	6.35E+10	5.72E+10	5.72E+10	-9.51E+09
Elementary sulfur [g]	4.29E+10	5.13E+10	-1.38E+10	0.00E+00	2.74E+10	2.74E+10	2.47E+10	2.47E+10	-4.11E+09
By-product:									
Gypsum (CaSO$_4$ · 2H$_2$O) [g]	1.15E+10	1.37E+10	-3.68E+09	0.00E+00	7.33E+09	7.33E+09	6.61E+09	6.61E+09	-1.10E+09
Exhaust gas volume [m³ i. N.]	1.39E+11	1.66E+11	-4.47E+10	0.00E+00	8.90E+10	8.90E+10	8.03E+10	8.03E+10	-1.33E+10
Air emissions:									
CO [g]	7.78E+10	2.64E+10	-7.50E+10	-1.67E+09	1.69E+10	1.69E+10	5.18E+10	5.18E+10	1.19E+11
CO$_2$ [g]	2.80E+13	3.34E+13	-8.95E+12	-1.79E+11	1.77E+13	1.77E+13	1.59E+13	1.59E+13	-2.74E+12
CO$_2$ equivalent [g]	0.00E+00	0.00E+00	0.00E+00	-1.22E+11	-1.44E+11	-1.44E+11	-8.92E+10	-8.92E+10	0.00E+00
SO$_2$ [g]	2.71E+10	1.89E+10	-5.08E+09	-5.36E+08	9.55E+09	9.55E+09	8.61E+09	8.61E+09	9.45E+09
H$_2$S [g]	0.00E+00	0.00E+00	0.00E+00	-2.94E+05	-2.94E+05	-2.94E+05	-1.76E+05	-1.76E+05	0.00E+00
NO$_x$ [g]	3.04E+11	2.86E+11	5.77E+11	1.11E+12	1.14E+12	9.70E+11	3.49E+11	2.97E+11	1.77E+11
NH$_3$ [mg]	1.56E+09	1.86E+09	-5.00E+08	-5.54E+12	-6.58E+12	-6.58E+12	-4.07E+12	-4.07E+12	-1.49E+08
HCN [g]	0.00E+00	0.00E+00	0.00E+00	-6.30E+02	-6.30E+02	-6.30E+02	-3.77E+02	-3.77E+02	0.00E+00
MEA [g]	0.00E+00	0.00E+00	0.00E+00	-2.22E+06	-2.22E+06	-2.22E+06	-1.33E+06	-1.33E+06	0.00E+00
N$_2$O [g]	1.61E+07	1.92E+07	-5.15E+06	0.00E+00	1.03E+07	1.03E+07	9.26E+06	9.26E+06	-1.54E+06
CH$_4$ [g]	1.52E+09	7.19E+08	-3.18E+09	-1.44E+09	-1.44E+09	-1.44E+09	1.02E+09	1.02E+09	2.15E+09
NMVOC [g]	3.58E+10	6.86E+09	-1.00E+11	1.47E+10	1.62E+10	1.46E+10	7.05E+10	6.34E+10	7.21E+10
H$_2$O evaporation [g] (only secondary)	8.87E+11	1.06E+12	-2.85E+11	0.00E+00	5.67E+11	5.67E+11	5.12E+11	5.12E+11	-8.50E+10
Dust [g]	3.54E+08	4.23E+08	-1.14E+08	-1.10E+08	1.10E+08	1.10E+08	1.34E+08	1.34E+08	-3.39E+07
Particles [g]	1.61E+10	4.39E+09	6.05E+08	5.67E+09	2.07E+10	2.07E+10	1.23E+10	1.23E+10	1.23E+10
HCl [g]	2.94E+07	3.51E+07	-9.43E+06	-4.19E+06	1.45E+07	1.45E+07	1.43E+07	1.43E+07	-2.81E+06
HF [mg]	1.35E+09	1.61E+09	-4.33E+08	0.00E+00	8.62E+08	8.62E+08	7.77E+08	7.77E+08	-1.29E+08
Exhaust air from nuclear power station:									
Chimney escape air (exhaust air) [m³]	4.48E+07	5.36E+07	-1.44E+07	0.00E+00	2.87E+07	2.87E+07	2.58E+07	2.58E+07	-4.29E+06
Exhaust air content:									
Noble gases [Bq]	1.80E+11	2.15E+11	-5.78E+10	0.00E+00	1.15E+11	1.15E+11	1.04E+11	1.04E+11	-1.72E+10
Long-life aerosols (without Tritium) [Bq]	1.76E+05	2.10E+05	-5.65E+04	0.00E+00	1.13E+05	1.13E+05	1.02E+05	1.02E+05	-1.69E+04
Tritium [Bq]	2.15E+10	2.57E+10	-6.91E+09	0.00E+00	1.38E+10	1.38E+10	1.24E+10	1.24E+10	-2.06E+09
Iodine 131 [Bq]	1.08E+06	1.29E+06	-3.46E+05	0.00E+00	6.89E+05	6.89E+05	6.21E+05	6.21E+05	-1.03E+05
Waste water emissions:									
Waste water [g]	3.54E+11	4.23E+11	-1.14E+11	0.00E+00	2.26E+11	2.26E+11	2.04E+11	2.04E+11	-3.39E+10
DeSOx water [g]	1.06E+11	1.27E+11	-3.41E+10	0.00E+00	6.80E+10	6.80E+10	6.13E+10	6.13E+10	-1.02E+10
Waste water emissions after biological refinery clarification plant [g]:	2.51E+12	2.99E+12	-8.04E+11	0.00E+00	1.60E+12	1.60E+12	1.44E+12	1.44E+12	-2.40E+11
Oil content [g]	7.46E+07	8.91E+07	-2.39E+07	-1.09E+07	3.52E+07	3.52E+07	3.54E+07	3.54E+07	-7.15E+06
CSB [g]	2.00E+08	2.39E+08	-6.43E+07	-1.18E+05	1.28E+08	1.28E+08	1.15E+08	1.15E+08	-1.92E+07
BSB$_5$ [g]	3.76E+07	4.49E+07	-1.21E+07	0.00E+00	2.40E+07	2.40E+07	2.17E+07	2.17E+07	-3.60E+06
Precipitation materials [g]	7.52E+05	8.98E+05	-2.41E+05	0.00E+00	4.80E+05	4.80E+05	4.33E+05	4.33E+05	-7.20E+04
Ammonium nitrogen [g]	8.29E+06	9.91E+06	-2.66E+06	-1.52E+06	3.73E+06	3.73E+06	3.83E+06	3.83E+06	-7.94E+05
NO$_3$ [g]	0.00E+00	0.00E+00	0.00E+00	-5.74E+05	-5.74E+05	-5.74E+05	-3.44E+05	-3.44E+05	0.00E+00
Phosphate [g]	0.00E+00	0.00E+00	0.00E+00	-4.76E+04	-4.76E+04	-4.76E+04	-2.85E+04	-2.85E+04	0.00E+00
Sulfate [g]	1.26E+08	1.51E+08	-4.05E+07	-5.40E+09	-5.32E+09	-5.32E+09	-3.17E+09	-3.17E+09	-1.21E+07
Chloride [g]	2.18E+09	2.60E+09	-6.99E+08	-5.15E+08	8.32E+08	8.32E+08	9.14E+08	9.14E+08	-2.09E+08
Aromatic hydrocarbon [g]	4.48E+06	5.35E+06	-1.44E+06	-1.33E+05	2.73E+06	2.73E+06	2.50E+06	2.50E+06	-4.29E+05

Reference data	Actual, 1995	K, 2010	K+EU3M, 2010	V₁, 2010	V₂, 2010	V₂, SP, 2010	V₃, 2010	V₃, SP, 2010	V₄, 2010
Heavy duty vehicles > 14 [t] permissible total weight	Reference year	Reference measure	Total	Total	Total	Sensitivity test	Total	Sensitivity test	Total
Iron [g]	0.00E+00	0.00E+00	0.00E+00	-2.75E+09	-2.75E+09	-2.75E+09	-1.64E+09	-1.64E+09	0.00E+00
Titanium [g]	0.00E+00	0.00E+00	0.00E+00	-6.60E+02	-6.60E+02	-6.60E+02	-3.95E+02	-3.95E+02	0.00E+00
Vanadium [g]	0.00E+00	0.00E+00	0.00E+00	-1.03E+04	-1.03E+04	-1.03E+04	-6.17E+03	-6.17E+03	0.00E+00
Tungsten [g]	0.00E+00	0.00E+00	0.00E+00	-6.45E+02	-6.45E+02	-6.45E+02	-3.86E+02	-3.86E+02	0.00E+00
Zinc [g]	0.00E+00	0.00E+00	0.00E+00	-1.20E+05	-1.21E+05	-1.21E+05	-7.28E+04	-7.28E+04	0.00E+00
Sodium [g]	0.00E+00	0.00E+00	0.00E+00	-5.25E+06	-5.25E+06	-5.25E+06	-3.14E+06	-3.14E+06	0.00E+00
Waste water from nuclear power station:									
Waste water drainage [g]	2.14E+08	2.56E+08	-6.88E+07	0.00E+00	1.37E+08	1.37E+08	1.24E+08	1.24E+08	-2.05E+07
Waste water content:									
Splitting and activating products (without Tritium) [Bq]	6.83E+06	8.16E+06	-2.19E+06	0.00E+00	4.37E+06	4.37E+06	3.94E+06	3.94E+06	-6.54E+05
Tritium [Bq]	2.09E+11	2.49E+11	-6.70E+10	0.00E+00	1.33E+11	1.33E+11	1.20E+11	1.20E+11	-2.00E+10
Waste:									
Recycling [g]	0.00E+00	0.00E+00	0.00E+00	-6.63E+08	-6.63E+08	-6.63E+08	-3.97E+08	-3.97E+08	0.00E+00
Reusing [g]	0.00E+00	0.00E+00	0.00E+00	-1.03E+10	-1.03E+10	-1.03E+10	-6.18E+09	-6.18E+09	0.00E+00
Ash [g]	3.02E+10	3.60E+10	-9.68E+09	0.00E+00	1.93E+10	1.93E+10	1.74E+10	1.74E+10	-2.89E+09
Inert material tip [g]	1.02E+10	1.22E+10	-3.29E+09	-1.39E+10	-8.06E+09	-8.06E+09	-2.94E+09	-2.94E+09	-9.81E+08
Residue material tip [g]	1.24E+09	1.48E+09	-3.99E+08	-3.00E+08	4.72E+08	4.72E+08	5.20E+08	5.20E+08	-1.19E+08
Reactor tip [g]	3.96E+07	4.73E+07	-1.27E+07	-3.97E+07	-1.51E+07	-1.51E+07	-1.44E+06	-1.44E+06	-3.79E+06
Boiling waste to recycling plant [g]	1.85E+07	2.21E+07	-5.93E+06	-5.80E+08	-5.70E+08	-5.70E+08	-3.38E+08	-3.38E+08	-1.77E+06
Special waste to special recycling plant [g]	3.53E+08	4.22E+08	-1.13E+08	-5.73E+07	1.67E+08	1.67E+08	1.69E+08	1.69E+08	-3.38E+07
Land farming [g]	5.25E+08	6.27E+08	-1.68E+08	-9.37E+07	2.30E+08	2.30E+08	2.38E+08	2.38E+08	-5.02E+07
Radioactive deposits/factory waste									
Burned off nuclear fuel [kg]	1.26E+03	1.50E+03	-4.03E+02	0.00E+00	8.03E+02	8.03E+02	7.24E+02	7.24E+02	-1.20E+02
Composition [kg]									
uranium	1.19E+03	1.42E+03	-3.81E+02	0.00E+00	7.58E+02	7.58E+02	6.84E+02	6.84E+02	-1.14E+02
Plutonium	1.28E+01	1.53E+01	-4.10E+00	0.00E+00	8.16E+00	8.16E+00	7.36E+00	7.36E+00	-1.22E+00
Split products	5.77E+01	6.90E+01	-1.85E+01	0.00E+00	3.69E+01	3.69E+01	3.33E+01	3.33E+01	-5.53E+00
Weak and medium active solid material [kg]	2.59E+03	3.09E+03	-8.30E+02	0.00E+00	1.65E+03	1.65E+03	1.49E+03	1.49E+03	-2.48E+02
Weak and medium active waste (total)									
Ball resins [Bq]	2.40E+11	2.86E+11	-7.69E+10	0.00E+00	1.53E+11	1.53E+11	1.38E+11	1.38E+11	-2.29E+10
Filter cartridge inserts [Bq]	2.40E+10	2.86E+10	-7.69E+09	0.00E+00	1.53E+10	1.53E+10	1.38E+10	1.38E+10	-2.29E+09
Thick-walled metal parts, building waste [Bq]	2.40E+10	2.86E+10	-7.69E+09	0.00E+00	1.53E+10	1.53E+10	1.38E+10	1.38E+10	-2.29E+09
Evaporation concentrate [Bq]	1.44E+11	1.72E+11	-4.61E+10	0.00E+00	9.19E+10	9.19E+10	8.29E+10	8.29E+10	-1.38E+10
Thin-walled metal parts, building waste [Bq]	3.35E+10	4.01E+10	-1.08E+10	0.00E+00	2.14E+10	2.14E+10	1.93E+10	1.93E+10	-3.21E+09
Sludge [Bq]	2.18E+10	2.61E+10	-7.00E+09	0.00E+00	1.39E+10	1.39E+10	1.26E+10	1.26E+10	-2.09E+09
Paper, textiles, plastics [Bq]	1.17E+09	1.40E+09	-3.77E+08	0.00E+00	7.51E+08	7.51E+08	6.77E+08	6.77E+08	-1.12E+08
Oils [Bq]	4.79E+04	5.73E+04	-1.54E+04	0.00E+00	3.06E+04	3.06E+04	2.76E+04	2.76E+04	-4.59E+03
Radiation or exposed persons in nuclear power stations [man Sievert per annum]	2.25E-02	2.69E-02	-7.23E-03	0.00E+00	1.44E-02	1.44E-02	1.30E-02	1.30E-02	-2.16E-03